Structural Stability Analysis of a Quartz Fiber Optic Coupler Under Thermal Loading

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One of the most difficult barriers in high–lumen, high wattage fiber optic lighting is coupling to light guides efficiently without allowing the high lamp temperature to affect the structural stability of the light guide. Lawrence Berkeley National Laboratory's Lighting Systems Research Group is currently developing a novel fiber optic coupler that will employ a variety of high–wattage electrodeless lamps. The goal of the project is to use an electrodeless lamp in a coupler whose design is based entirely on the principle of total internal reflection, as demonstrated in **Figure 1**.[1]

In the coupling system shown in **Figure 1** , an electrodeless lamp built into the quartz coupler guides the light from the lamp to the acrylic fiber optic light guides. A major concern with this design is the structural stability of the material surrounding the lamp, since the extreme heat of lamp could cause most plastic or glass materials to melt or crack. The typical operating temperatures of electrodeless lamps range from 800–900°C.[2] Many lighting and glass experts recommended quartz as the material of choice for the coupler because of its resilient thermal properties and ability to transmit visible light efficiently.

Even though most lighting and glass specialists were confident in the stability of quartz, a few questioned its structural stability in close proximity to lamps that could reach temperatures of up to 900°C. To address these concerns, the Lighting Systems Research Group performed a detailed thermal analysis of quartz at temperatures between 850 and 1090°C. For this analysis we employed: (1) theoretical computer models; (2) physical quartz models with heating coils to simulate the lamp; (3) computer models based on collected data; and (4) infrared thermographs. The purpose of this research was to determine if quartz remains structurally stable in the coupler situation shown in **Figure 1** , or if it will crack or melt due to the thermal load. We also wanted to determine the distance that plastic light guides must be placed from the light source to avoid melting from the heat of the quartz. Ideally, the light guides will be placed in direct contact with the quartz coupler as shown in **Figure 1** . This paper describes the results of these tests and the conclusions drawn from the compiled data.

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Background

Two methods of modeling the thermal effects on quartz were used: computer simulation models and a physical quartz model. First, an initial computer model was created to get a general idea of how quartz would react to a small, centralized heat source. After this model predicted that quartz could dissipate the heat well enough to avoid any thermal strain (cracking or melting due to extreme heat), a quartz model was constructed.

A platinum wire coil inside the quartz model simulated the heat generated by an electrodeless lamp. The coil was heated to the approximate temperature of an electrodeless lamp (about 850°C) by placing a dc voltage across the wire coil. Measurements were also made at coil temperatures of up to 1090°C to ensure the stability of quartz at the most extreme temperatures it might endure. During the tests performed with the quartz model, five thermocouples measured the temperature at various points along the coupler. Thermocouple readings were taken as the model heated and also at the stabilized temperature. From the thermocouple measurements, a final computer model was generated. This computer model interpolated the temperatures between the points measured by the thermocouples in the physical model tests.

The final step in the analysis was to take infrared thermographic images of the quartz model. Thermographic images were taken as the model heated to stabilization with the platinum wire coil reaching a stabilized temperature of approximately 850°C. These images were then compared with the results of the computer models to confirm the accuracy of the models and the earlier laboratory measurements.

Computer modeling

Computer models were used to make theoretical pre-

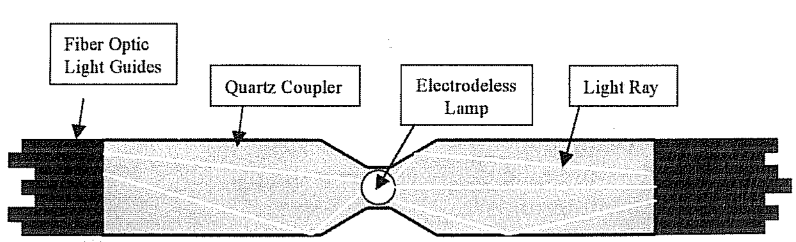

Figure 1—LBNL's Fiber Optic Coupling System (concept illustration).

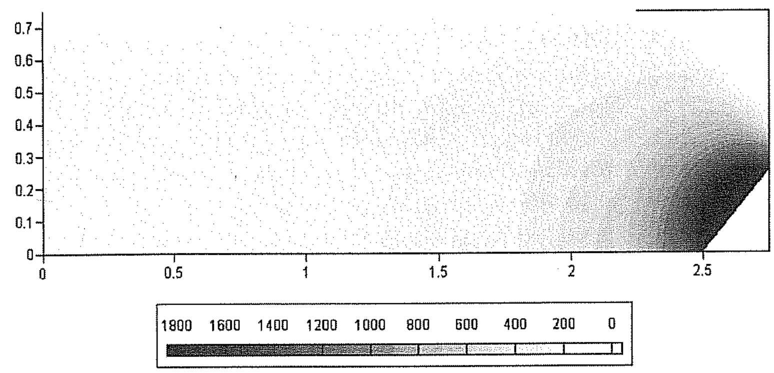

Figure 2—Cross-section of the initial computer model (this figure shows only the upper left quarter of the model).

dictions about the effect of heat on a large, solid piece of quartz, as will be used for the coupler. These models were generated in HEATING (acronym for Heat Engineering and Transfer In Nine Geometries), a thermal modeling software program that solves both steady state and transient thermodynamics problems in up to three dimensions. The first step in the thermodynamic analysis of the coupler system was assuring that the lamp and coupler would be a steady state system. A complex finite difference analysis was necessary to accurately determine the steady state of the coupler model, because of the complex shape of the model and the three™dimensional heat transfer.

HEATING generated the steady state models of the coupler system in cylindrical (r-z-θ) coordinates (demonstrated in **Figure 2**). Since it was assumed that the thermal distribution would be axi-symmetric for θ and the plane of symmetry is along the z-axis, only one-quarter of the coupler was modeled. The following assumptions were made about the coupler when generating all computer models: (1) the inside surface temperature of thelamp in the quartz is constant; (2) the heat transfer throughout the quartz is conductive; and (3) heat is transferred from quartz to the ambient environment (air) by radiating and convective mechanisms according to the equation:

$$q = h_{eff}A(T_s - T_b)$$

$$\text{where } h_{eff} = h_r(T_s^2 + T_b^2)(T_s - T_b) + h_n - T_b)^{he}$$

In the first equation, h_{eff} is the effective film coefficient; A is the surface area; and T_s and T_b are surface and boundary temperatures, respectively. In the second equation, h_r is the coefficient for radiation, which is easily calculated knowing the emissivity of quartz; h_n is the natural convection multiplier term; and he is the natural convection exponent term.

Initial computer models

The initial computer models were used only as an indication of how a quartz rod dissipates heat from a small, centralized source. The results obtained from these models were only estimates, since a measured natural convection heat transfer coefficient value was not yet available for heat flowing from the surface of the quartz to the ambient environment. The results of the initial models are shown in **Figure 2**. Only one-quarter of the coupler is modeled since all other sections are assumed to be symmetrical.

Analysis of initial thermal model

The maximum recommended temperature for prolonged use of quartz is 1000°C and the strain point (point at which deformation may begin to occur) is 1075°C.[3] The strain point is approximately 200 degrees higher than the operating temperature of the electrodeless lamps that will be used in the coupler. The model predicts that the quartz will dissipate heat quickly down its length and without trapping heat at any point. There is no point on the stabilized computer model that reaches temperatures higher than the lamp. Therefore, the model predicts that temperatures throughout the model should remain safely below the strain point. Of even greater importance, the model's temperature gradient shows that, in the region closest to the lamp, the temperature drops off very rapidly in the coupler. This means that the quartz dissipates heat well near the lamp so the plastic fiber optics at either end of the coupler will be subjected to minimal conductive heating, which could destroy the fiber.

Quartz model analysis using thermocouples

Once the initial computer models gave some indication that the quartz could dissipate heat well enough to withstand thermal strain or melting, an actual quartz model of the coupler was fabricated. A coiled platinum

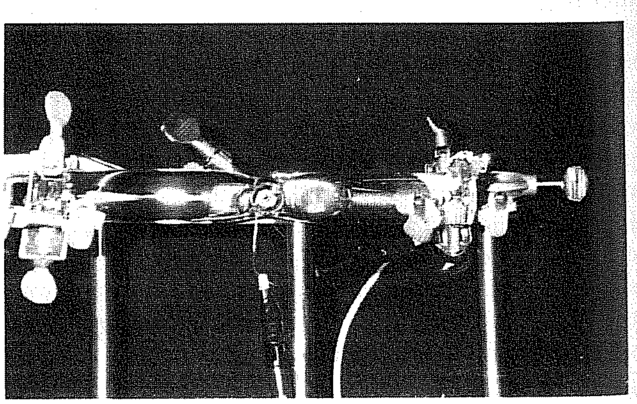

Figure 3—Photograph of quartz model with coiled platinum wire at center.

wire was used to simulate the heat produced by a lamp in the model coupler. A photograph of the model is shown in **Figure 3** . The model is 18-cm long with a 2.5-cm diameter at the ends and a 2 cm diameter at the center. The platinum wire fits in a 1 cm diameter hole at the center of the model. General Electric Type 214 quartz was used for the model.

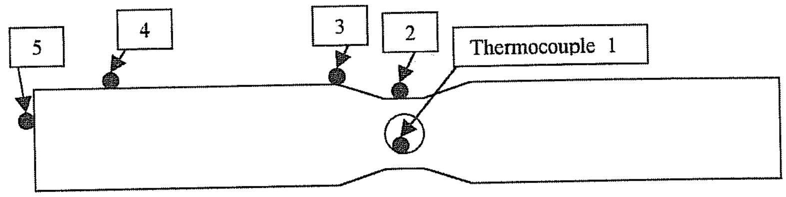

Figure 4—Placement of thermocouple on quartz model (not to scale; only approximate locations given).

First series of tests

In the first tests performed with the model, five thermocouples were placed at various points along the length of the model just touching the surface of the quartz (not embedded). A dc voltage applied across the platinum wire coil heated it to the approximate temperature of an electrodeless lamp. One thermocouple measured the temperature of the platinum wire coil and the other four measured the temperature of the quartz and various distances from the coil. **Figure 4** shows the location of the five thermocouples on the model and **Table 1** presents the results from two tests performed with the model.

The transient temperatures of the model, before it reached stabilization, were also monitored. The measurements show a rapid increase in quartz and coil temperature for the first 45 sec. During this period, the area within 1 cm of the wire coil heated at a rate of several degrees per second, an acceptable and non-damaging heat transfer rate for quartz. In the following 9–11 min, the temperature of the model increased more slowly until the coil and model temperatures stabilized. The time to stabilization was approximately 12 min in most cases.

When comparing the measured and predicted temperatures of the stabilized model, the measured results differ slightly from the initial computer models. This discrepancy was most probably due to the rough estimation of enthalpy values in the initial computer model.

Another discrepancy between the measured and predicted temperatures occurred at thermocouple 5 in the actual model. The higher measured temperature is probably due to the thermocouples measuring additional infrared and visible radiation totally internally reflected by the quartz model.

Also, some error may have been introduced because the contacts between the thermocouples and the quartz were not secured with thermocouple gel (which is unavailable for such high temperature use). This may have caused temperature readings to vary slightly between tests. This is the most probable explanation for the lower temperature read by thermocouple 2 in the 1090°C test.

Second series of tests

A second series of tests were performed at temperatures between 850 and 900°C. The primary purpose of the tests was to isolate and eliminate the problems and discrepancies encountered in the first round of tests; namely, problems with moving thermocouples and concentrated IR and visible radiation at thermocouple 5. The position of the thermocouples was carefully monitored to be sure they were properly positioned and did not change position during testing. For the first few tests, all thermocouples were in the same locations as in the first round of tests, as shown in **Figure 4** . The results of these tests are given in **Table 2**

Once again, the readings from thermocouple 5 were higher than expected. To test our theory that these higher than expected measurements were caused by total internally reflected light being focused on thermocouple 5, we tried to shield the thermocouple from the extra radiation by moving it slightly.

Thermocouple 5 was moved from its position at the end of the coupler to a location at the outside edge of

Table 1—Thermocouple readings of two tests using the quartz model heated by coiled platinum wire.

temperature	Platinum coil temperature = 915°C	Platinum coil temperature = 1090°C
Thermocouple	Temperature (°C)	Temperature (°C)
#1	915	1090
#2	463	455
#3	118.3	130.5
#4	9.9	42.3
#5	98.5*	

*Unavailable because the thermocouple shifted during testing.

Table 2—Thermocouple readings for the second series of tests (positions of the thermocouples are given in Figure 5).

temperature	Platinum coil temperature = 915°C	Platinum coil temperature = 1090°C
Thermocouple	Temperature (°C)	Temperature (°C)
#1	855	879
#2	320	454
#3	138	151
#4	50	72.1
#5	44.5	67

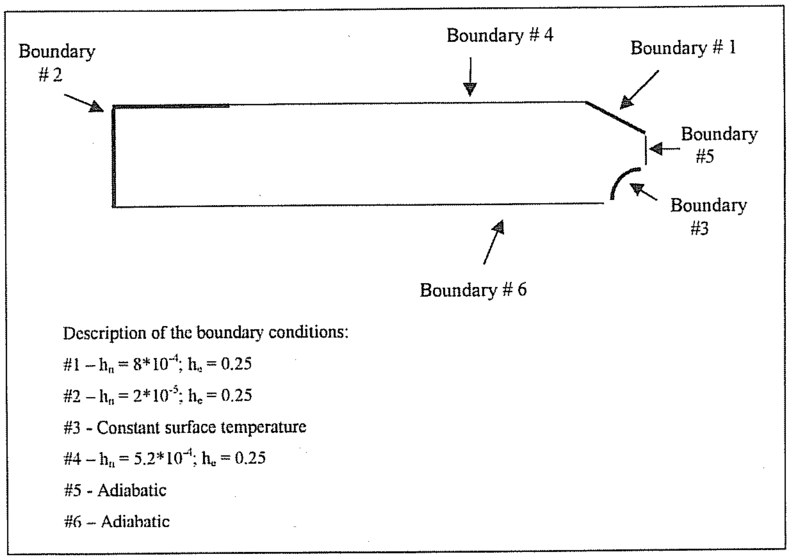

Figure 5—Heat transfer coefficient (h) calculation results based on thermocouple measurements.

the coupler's to pinpoint the differences in temperature readings caused by additional radiation. In this position the thermocouple was no longer being exposed to the additional radiation totally internally reflected to the end of the coupler. We found that the thermocouple reading dropped from 67 to 41°C immediately. This test was repeated with a different thermocouple and similar results were obtained, the temperature reading dropped from 56 to 38°C.

Discussion of thermocouple tests

With the second series of tests, we were able to pinpoint the cause of the high temperature reading on thermocouple 5. By moving the thermocouple only a few millimeters to the side of the coupler near the end instead of directly on the coupler's end, we found that the temperature dropped to a reasonable and predictable temperature.

We were also able to take more accurate measurements in the second series of tests by more closely monitoring the positions of the thermocouples to be sure they did not shift during testing—a problem we encountered during the first series.

The data gathered from the thermocouples confirm that the temperature of the quartz drops off rapidly as the distance from the heated wire coil increases—the trend forecasted by the initial computer models. At the ends of the coupler farthest from the lamp, the coupler temperature was nearly room temperature. With a thin IR blocking coating on the coupler's end, plastic fiber optics should not melt when in contact with the coupler.

Final computer models

Once measured values were available from the first series of tests on the quartz model, numerous iterative computations were made to determine the value of the natural convection multiplier term, h_n. The h_n values were set for a coil temperature of 915°C, and then the same values were used when modeling a coil temperature of 1090°C. Accurately determining this value through iterative computer modeling allowed us to create a much more reliable model of the temperature gradient in the quartz coupler.

When calculating the value of h_n, the higher than expected temperature measured by thermocouple 5 was discarded, because the increase was due to additional radiation directed from the platinum coil. This radiation did not cause an increased temperature in the quartz itself. Also, the new computer model calculations accounted for the discrepancy between the two thermocouple 2 readings. By discarding the erroneous readings (proven to be erroneous with a second series of tests as discussed above), the final computer model predicts more reasonable temperatures than the thermocouple measurements. The predicted values for h in the final computer model are summarized in **Figure 5**. Also given is the natural convection exponent term, h_e, which was set to 0.25 for all laminar (non™fluctuating fluid flow) regions as suggested by *ASHRAE Handbook of Fundamentals*. Please note that the boundary lines are shown with different thickness, indicating a change in h_n value. The numbers in circles

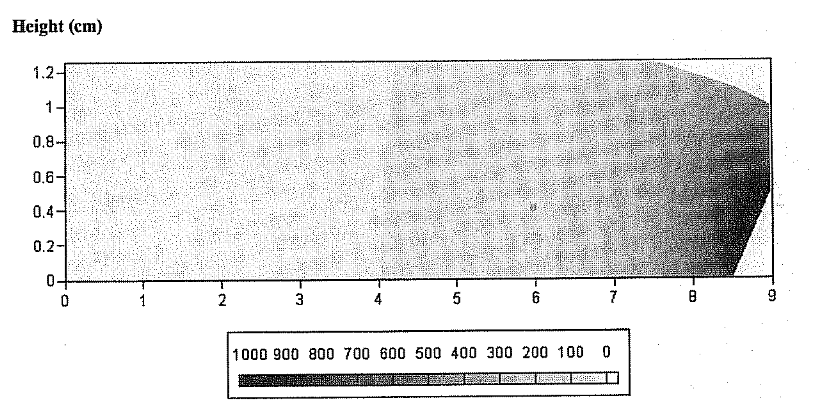

Figure 6—Final computer model for platinum wire coil temperature of 915°C (upper left quarter of model is shown).

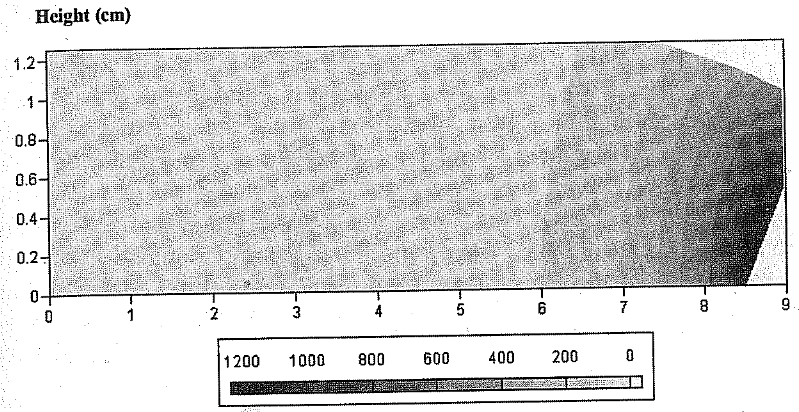

Figure 7—Final computer model for platinum wire coil temperature of 1090°C (upper left quarter of model is shown).

point to where temperatures were measured.

Table 3 presents the calculated results from the final computer model compared with the temperatures measured by the thermocouples. The calculated temperatures matched the accurately measured values within 3 percent. Also included in the table is one set of measurements from the second series of tests when thermocouple 5 was moved away from the concentrated radiation at the end of the coupler. The trends in the computer model match the measured results from the second series of tests very closely. **Figures 6** and **7** show the final computer models obtained from the newly calculated heat transfer coefficient. One model was made for each of the first series thermocouple tests: one at 915°C and one at 1090°C. Once again, only one-quarter of the coupler was modeled and it is assumed that the other portions behave in a symmetrical manner.

Thermographic imaging of quartz model

As a check of the interpolated values found in the final computer model, infrared thermographic images of the quartz model were made. More accurate and detailed information on the transient state of the model was obtained from these tests because images were taken every 12 sec after current was applied to the platinum wire coil. **Figure 7** shows a chronological series of thermographs as well as a thermograph of the stabilized model at approximately 850°C (coil temperature reading in thermographic image).

The stabilized thermograph in **Figure 7** (given on the final page) matches the final computer model very closely. The platinum wire coil was about 50 degrees cooler during the thermographic imaging than the lamp temperature assumed in the computer model. But when comparing the two models, the temperature drops off in a very similar gradient in both. This comparison is shown in **Figure 8**, which graphs the results of both the computer model and IR images. The graph plots only the 4 cm closest to the light source, where the largest temperature fluctuations occur.

Summary

When the Lighting Research Group began the development of a new fiber optic coupler that would employ high wattage, high-lumen lamps, the structural stability of the material close to the lamp was a primary concern. The temperature gradient along the length of the coupler was also very important because the distance the plastic fibers must be from the lamp to prevent melting is of critical importance in the final design.

Lighting and glass experts recommended that quartz

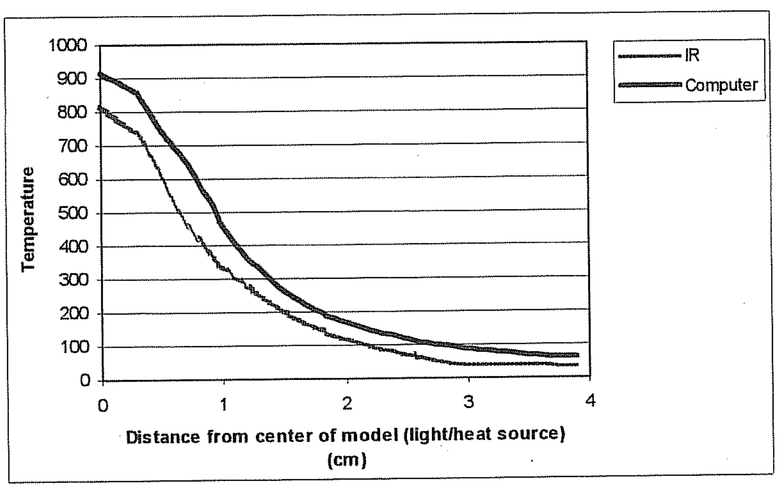

Figure 8—Comparison of IR thermography temperature measurements and the 915°C computer model predicted temperatures.

Table 3—Comparison of temperatures measured by thermocouples and calculated temperatures (all temperatures given in degrees celsius)

Thermocouple	Coil temp. = 915°C Measured temp	Coil temp. = 915°C Calculated temp	Coil temp. = 1090°C Measured temp	Coil temp. = 1090°C Calculated temp	Coil temp. = 868°C Second series test measured temp
#1 (coil temp.)	915	915	1090	1090	868
#2	463	462	455	550	385
#3	118.3	115	130.5	133	166
#4	39.9	40.2	42.3	43	61.9
#5	98.5	37.3	unavailable	39	40.8

be used for the coupler. Since some doubts still remained about the structural stability of quartz surrounding lamps with an operating temperature of up to 900°C, the Lighting Systems Research Group performed the described thermal analyses.

First, an initial computer model was developed which predicted that quartz quickly dissipates the heat of a lamp. Then a quartz model was fabricated and a platinum wire coil simulated the heat of the lamps at the center of the model coupler. Even when this model was heated to 1090°C, well above the standard operating temperature of electrodeless lamps, the quartz remained thermally stable and dissipated heat well throughout the model. Another important finding was that at either end of the model the quartz temperature was low enough (only a few degrees above room temperature) to prevent plastic light guides from melting when in direct contact with the coupler. A final computer model used a newly calculated natural convection multiplier term (h_n) which was obtained from the quartz model tests. The final computer model more reliably showed the heat dissipation gradient of the quartz and confirmed that the quartz could dissipate the heat of a lamp rapidly enough to avoid thermal strain.

Finally, to check the results of the new computer model, thermographic images were made of the quartz model. The thermographic images showed, once again, that the quartz coupler quickly dissipates heat and remains at temperatures well below its strain point. With closer analysis it was found that the temperatures shown in the thermographic images matched thecomputer models' predicted temperature gradient very closely.

Conclusions

From both the computer and physical models, it is clear that the quartz coupler will remain structurally stable and avoid thermal strains for electrodeless lamps with temperatures below the recommended maximum operating temperature of quartz (1000°C). This is true for both the transient warm-up period and for the final steady state temperature of the quartz coupler. Further, since the quartz is able to dissipate the heat so quickly, the plastic fiber optics attached to either end of the coupler will encounter a minimal amount of conductive heat from the lamp. This important finding means that plastic fiber optics could be a viable light guide from the quartz coupler.

It was also found that the computer models closely matched the measured temperature readings of the quartz coupler and presented more detailed information on the predicted temperature gradient. Therefore, we can conclude that computer models could be used as a stand-alone method for estimating the heat transfer of similar-geometry quartz couplers. For example, furthercomputer models could determine the minimum length of quartz needed to prevent plastic light guides from melting.

Acknowledgments

Tom Orr, LBNL's Scientific Glass Blower, constructed the quartz coupler model and many platinum wire coils. Mr. Orr also provided extensive information on the thermal properties of quartz. The LBNL Infrared Thermography Lab created the thermographic images used in this report. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, U.S. Department of Energy, Office of Building Technology, State and Community Programs, Office of Building Equipment under Contract Number DE-AC03-76F00098.

References

1. Siminovitch, M. 1994. High efficiency coupling system forfiber optic and solid light guide illuminating systems. Patent Pending, LBNL Invention Disclosure/DOE case #1B750.

2. Lapatovitch, W. 1997. Physicist, new light sources personal communication. Beverly, MA: OSRAM SYLVANIA Research and Development Center.

3. Heraeus, Q., 1979. Fused quartz and fused silica for optics. *Product Specifications Catalogue*

4. Graves, R.S. and Zarr, R.R. 1997. American Society for Testing and Materials . STP 1320.

5. Turler, D., Griffith, B.T., Arasteh, D.K. 1997. Laboratory procedure for using infrared thermography to validate heat transfer models. Insulation Materials: Testing and Applications, Third Volume. ASTM: 23–45.

Discussions

In general I found the paper to be competent in its presentation of an analysis involving theoretical as well as experimental results. In general, the danger of computer models that are optimized based on experimentation is the predicted results are then only as valid as the experimentation involved. Specifically, the following concerns are left unanswered:

1. One of the goals of the paper was to determine the distance that plastic light guides must be placed from the light source to avoid melting. However, in the body of the paper, the melting point of plastic fiber is never addressed. Furthermore, an effort is made in the paper to avoid the additional heating due to direct illumination of thermocouple number five. In fact, this direct illumination is deemed erroneous and the thermocouple moved. However, in a real world application where a plastic fiber is placed at the end of the coupling system, the fiber would indeed see this additional radiation. And in fact it may be necessary to consider this.

2. The paper fails to address or account for the potential of failure due to surface or subsurface damage of the quartz, and its potential contribution.

3. The paper fails to address or account for the impact of the presence of microwaves needed for electrodeless lamps and their component contribution.

Other than these points, the paper presents sound results of a computer model verified and optimized based on experimentation.

JonNisper
Remote Source Lighting

The concept of using an embedded high intensity discharge lamp inside an optical coupler to maximize fiber optic injection efficiency is interesting. The author provides convincing evidence to support the hypothesis that vitreous silica (commonly called quartz) is a suitable material for such a device.

A major concern of such a proposed device is the amount of power, which is conducted away by the quartz coupler from the discharge. The device is essentially a large heat sink attached to the lamp envelope. Can the author comment on the amount of power delivered to the platinum coils to raise the temperature of the "lamp" pocket to the suggested 900 °C?

The author uses a combination of units in inches, centimeters, Fahrenheit, and Celsius temperature scales. It is good practice to use consistent units. Further, the computer model in **Figure 3** is for a coupler about 3.8 cm in diameter and 14 cm long, although the manufactured prototype is 2.5 cm in diameter and 18 cm long. In subsequent figures of the computer modeling the dimensions are consistent with the prototype. Why was the first model different from the subsequent calculations?

Did the author attempt to experimentally verify that the output face of the coupler would successfully mate with a polymer light guide without melting and adhesion of the plastic to the quartz?

Dr. W. Lapatovitch

Authors' response

To Jon Nisper

Thank you for your insightful comments on the paper. Your three stated concerns are valid to the overall project of developing the fiber optic coupler in question.

1. The suggested maximum operating temperature for the type of plastic optic we are considering is approximately 100°C. In this paper we concentrated solely on the temperature of the quartz without considering the affect of infrared radiation from the light source directed onto the fiber optics. A method of filtering the infrared radiation requires further investigation before a prototype coupler can be built.

2. It was assumed in our investigation that future prototypes would be constructed of high-grade quartz and finished with the same detail as laboratory-quality lenses. Nevertheless, your comment on potential failure due to surface or subsurface damages brings to our attention an area that merits further investigation.

3. The models presented in this paper did not account for the presence of microwaves incident on the coupler. Future computer models will be more inclusive and will account for the effect of the radiation necessary for electrodeless lamp coupling.

To Dr. W. Lapatovitch

Thank you for your careful consideration of the paper. Your comments raised important points that will add clarity. When the coil reached 900°C, the power being delivered to the coil was 380 W dc (17.5 V dc at 0.8 Ohms resistance). We apologize for any confusion caused by the use of both SI and English units. The initial computer model was completed in English units before the quartz model was ever built. Instead of basing the quartz model on the size chosen for the initial computer model, the size was determined by the size and shape of quartz available at our laboratory. That is why the initial model is a different size. All subsequent measurements of length and temperature were made in the preferred SI system. To answer your final question, we did not attempt to couple the plastic optics to the ends of the quartz model. Even though the temperature of the quartz was cool enough for the plastic optics, we predicted that the infrared radiation from the heat source would have burned the light guides. Finding a suitable method of filtering the IR radiation will be addressed in future research.